CLAIMS

What is claimed is:

1. A test circuit comprising:

a primary winding having parallel extended portions for imposing a spatially periodic magnetic field of at least two spatial wavelengths in a test substrate when driven by an electric current;

an array of sensing elements for sensing the response of the test substrate to the imposed magnetic field, at least one sensing element positioned between the extended portions of a half wavelength of the primary winding located every other half wavelength of the primary winding, extended portions of the individual sensing elements being parallel to the extended portions of the primary winding; ~~and~~

a series connection between the sensing elements in every other half wavelength perpendicular to the extended portions of the primary winding to group the individual sensing elements, the series connection being in a different plane than the primary windings; and

separate output connections to each of plural groups of sensing elements located along the length of the extended portions of the primary winding.

2. A test circuit as claimed in Claim 1 wherein the individual sensing elements are located in at least two adjacent half wavelengths of the primary winding.

3. A test circuit as claimed in Claim 2 wherein the individual sensing elements in adjacent half wavelengths are spatially offset parallel to the extended portions of the primary winding.

4. A test circuit as claimed in Claim 3 wherein the spatial offset is one half the length of an individual sensing element parallel to the extended portions of the primary winding.

5. A test circuit as claimed in Claim 1 wherein all sensing elements are positioned at least one half-wavelength away from the ends of the extended portions of the primary winding.

6. A test circuit as claimed in Claim 2 further comprising additional conductors near the ends of the spatially offset sensing elements, along the length of the extended portions of the primary winding, to maintain the spatial periodicity of the conductors.

7. A test circuit as claimed in Claim 2 further comprising extensions of the endmost individual spatially offset sensing elements between the sensing elements in the adjacent half wavelength.

8. A test circuit as claimed in Claim 1 where one individual sensing element is located every other half wavelength to provide a single response.

9. A test circuit as claimed in Claim 1 where the sensing elements are in a different plane than the primary windings.

10. A test circuit as claimed in Claim 2 where the array of sensing elements has one individual sensing element located every other half wavelength but an array of sensing elements located in adjacent half wavelengths.

11. A test circuit as claimed in Claim 1 where every other half wavelength of the primary winding is connected together in series.

12. A test circuit as claimed in Claim 11 wherein a single pair of connector leads is connected to each set of primary winding half-wavelengths.

13. A test circuit as claimed in Claim 1 where the primary winding is distributed in two planes with extended portions of the primary windings located over one another and the connectors between the extended portions of the primary windings offset by one half-wavelength.

14. A test circuit as claimed in Claim 1 where each sensing element provides an absolute response.

15. A test circuit as claimed in Claim 1 where at least one of the sensing elements provides a differential response.

16. A test circuit as claimed in Claim 1 that is conformable to inspect curved parts.

17. A test circuit as claimed in Claim 1 placed on a curved and compliant substrate to inspect a curved part.

18. A test circuit as claimed in Claim 1 that is scanned across the surface of a part for the detection of flaws.

19. A test circuit as claimed in Claim 18 where the longest dimension of the flaw is substantially perpendicular to the extended portions of primary winding.

20. A test circuit as claimed in Claim 1 that is mounted against the surface of a part for detecting and determining the location of flaws.

21. A test circuit as claimed in Claim 20 where the longest dimension of the flaw is substantially perpendicular to the extended portions of primary winding.

22. A test circuit as claimed in Claim 1 where the lift-off is varied during calibration.

23. A test circuit as claimed in Claim 1 where the lift-off is varied during measurements.

24. A test circuit as claimed in Claim 1 where the part under test temperature is varied to vary the part conductivity for calibration.

25. A test circuit as claimed in Claim 1 where the part under test temperature is varied to vary the part conductivity for measurements.

26. A test circuit as claimed in Claim 1 where the part under test permeability is varied using a bias field during calibration.

27. A test circuit as claimed in Claim 1 where the part under test permeability is varied using a bias field during measurements.

28. A test circuit as claimed in Claim 1 where measurements are made at multiple operating conditions, including multiple lift-offs, temperatures, or bias fields.

29. A test circuit as claimed in Claim 1 where measurements grids with one or more dimensions are generated in advance and used as databases to look up and interpolate the electrical and geometric properties of interest at the location measured by each individual sensing element.

30. A test circuit as claimed in Claim 29 where the electrical and geometric properties at each sensing element location are correlated with dependent properties of interest.

31. A test circuit as claimed in Claim 29 where the array is scanned to build images of electrical properties across the surface of a part.

32. A test circuit as claimed in Claim 30 where multiple frequencies are used to measure property variations with depth at each sensing element.

33. A test circuit as claimed in Claim 31 where multiple frequencies are used to create three-dimensional images of properties.

34. An apparatus comprising:

a primary winding of parallel winding segments that impose a spatially periodic magnetic field, with at least two periods in a single plane, in a test substrate when driven by electric current;

one or more sensing windings that link flux over regions of incremental area along the length of a drive winding segment, with the sensing elements located in a second plane, with a series connection between sensing elements in every other half wavelength; and

leads to the sensing elements exiting the sensor footprint in a direction perpendicular to the direction of the drive winding segments.

35. A test circuit comprising:

a meandering primary winding having concentric substantially closed winding segments for imposing a spatially periodic magnetic field in the radial direction of at least two spatial wavelengths in a test substrate; and

at least one sensing element for sensing the response of the test substrate to the imposed magnetic field.

36. A test circuit as claimed in Claim 35, where the closed winding segments are circular.

37. A test circuit as claimed in Claim 35, where the closed winding segments follow a shape in the material under test.

38. A test circuit as claimed in Claim 35, with at least one sensing element positioned between the concentric circular segments of a half wavelength of the primary winding and located every other half wavelength of the primary winding, and with extended portions of the individual sensing elements concentric with the concentric circular segments of the primary winding.

39. A test circuit as claimed in Claim 38 where a single sensing element is placed within in each half wavelength of the primary winding.

40. A test circuit as claimed in Claim 39 where separate output connections are made to the sensing element in each half wavelength.

41. A test circuit as claimed in Claim 40 where at least two of the sensing elements are connected together to provide a common output.

42. A test circuit as claimed in Claim 41 where all of the sensing elements are connected together to provide single output.

43. A test circuit as claimed in Claim 42 where the sensing elements are in a different plane than the primary windings.

44. A test circuit as claimed in Claim 38 where the circumference of at least two half wavelengths of the primary winding is spanned by more than one sensing element and the sensing elements spanning the same angular dimensions in every other half-wavelength of the primary winding are connected together; and separate output connections are made to each group of sensing elements spanning the circumference of the primary winding.

45. A test circuit as claimed in Claim 44 where the sensing elements are connected together with a series connection.

46. A test circuit as claimed in Claim 45 where the series connections are in a different plane than the primary winding.

47. A test circuit as claimed in Claim 44 wherein the individual sensing elements are located in at least two adjacent half wavelengths of the primary winding.

48. A test circuit as claimed in Claim 47 wherein the individual sensing elements in adjacent half wavelengths are rotationally offset from one another.

49. A test circuit as claimed in Claim 48 wherein the rotational offset is one half the angle spanned by an individual sensing element.

50. A test circuit as claimed in Claim 49 further comprising extensions of the inner-most rotationally offset sensing elements between the sensing elements in the inner adjacent half wavelength.

51. A test circuit as claimed in Claim 38 where the sensing elements are in a different plane than the primary windings.

52. A test circuit as claimed in Claim 35 that is conformable to inspect curved parts.

53. A test circuit as claimed in Claim 35 placed on a curved and compliant substrate to inspect a curved part.

54. A test circuit as claimed in Claim 35 that is mounted against a surface of a part for the detection of flaws.

55. A test circuit as claimed in Claim 38 where the part under test temperature is varied to vary the part conductivity for calibration.

56. A test circuit as claimed in Claim 38 where the part under test temperature is varied to vary the part conductivity for measurements.

57. A test circuit as claimed in Claim 38 where measurements grids with one or more dimensions are generated in advance and used as databases to look up and interpolate the electrical and geometric properties of interest at the location measured by each individual sensing element.

58. A test circuit as claimed in Claim 57 where the electrical and geometric properties at each sensing element location are correlated with dependent properties of interest.

59. A test circuit as claimed in Claim 57 where the array is scanned to build images of electrical properties across the surface of a part.

60. A test circuit as claimed in Claim 58 where multiple frequencies are used to measure property variations with depth at each sensing element.

61. A test circuit as claimed in Claim 59 where multiple frequencies are used to create three-dimensional images of properties.

62. A test circuit as claimed in Claim 38 wherein the sensing windings link flux over regions of incremental area along the length of a drive winding segment, the sensing windings are located in a second plane with each sensing winding linking magnetic flux every other half period, and the leads to the sensing elements exit the sensor footprint radially, perpendicular to the direction of the drive winding segments.

63. A test circuit as claimed in Claim 38 further comprising a hollow center region for placement around a fastener shaft.

64. A test apparatus comprising:

concentric circular winding segments that impose a radial spatially periodic magnetic field, with at least two periods in a single plane, in a test substrate when driven by electric current; and

one or more sensing windings that link flux over each region bordered by the drive winding segments and concentric with the drive winding segments.

65. A test circuit comprising:

a primary winding of parallel extended winding segments that impose a spatially periodic magnetic field, with at least two periods, in a test substrate when driven by electric current;

an array of sensing windings for sensing the response of the test substrate to the imposed magnetic field, at least two of the sensing windings in different half-wavelengths of the primary winding linking incremental areas of the magnetic flux and being offset along the lengths of the parallel winding segments to provide material response measurements over different locations

when the circuit is scanned over the test material in a direction perpendicular to the extended winding segments; and

the sense windings confined to a single plane and the drive windings confined to a single plane.

66. A test circuit as claimed in Claim 65 wherein the parallel extended winding segments of the primary winding are formed by parallel extended portions of adjacent drive coils.

67. A test circuit as claimed in Claimed 66 wherein every other drive coil is connected in series on one side of the primary and the remaining drive coils are connected in series on the opposite side of the primary.

68. A test circuit as claimed in Claim 66 wherein a single pair of connector leads is connected to each set of primary winding half-wavelengths.

69. A test circuit as claimed in Claim 65 where the primary winding is distributed in two planes with extended portions of the primary windings located over one another and the connectors between the extended portions of the primary windings offset by one half-wavelength.

70. A test circuit as claimed in Claim 65 where the sensing windings linking incremental areas are located in every other half-wavelength while additional sensing windings that extend along a substantial length of the primary windings are located in the intermediate half-wavelengths of the primary winding.

71. A test circuit as claimed in Claim 70 where output connections of at least two of the sensing windings of substantial length are connected in series.

72. A test circuit as claimed in Claim 70 where extra conductors are placed in the endmost half-wavelengths, without secondary elements, to maintain the spatial periodicity of the conductors in the test circuit.

73. A test circuit as claimed in Claim 70 where extra conductors are placed at the ends of the sensing elements to maintain the spatial periodicity of conductors in the test circuit.

74. A test circuit as claimed in Claim 70 where the sensing windings linking incremental areas have extension loops on the winding side opposite the connector leads to provide essentially equivalent coupling of magnetic flux between offset sensing windings.

75. A test circuit as claimed in Claim 65 where the sensing windings are offset a distance one-half the length of extended portions of the sensing windings so that sensed responses cover overlapping areas.

76. A test circuit as claimed in Claim 66 where the array of sensing windings has at least one sensing coil every half wavelength, distance between sensing coils within an adjacent pair of extended portions being increased by the length of the sensing coils at least each half wavelength, each individual sensing coil having separate output connectors.

77. A test circuit as claimed in Claim 76 where the distance from the ends of the sensing coils to the connectors between the extended portions of the primary is kept essentially constant as the distance between the sensing coils is increased.

78. A test circuit as claimed in Claim 77 where the sensing coils provide an absolute response to the material properties.

79. A test circuit as claimed in Claim 77 where the sensing coils provide a differential response to the material properties parallel to the extended windings.

80. A test circuit as claimed in Claim 77 where the sensing coils in every other half wavelength provide an absolute response to the material properties while the sensing coils in the intermediate half meanders provide a differential response to the material properties parallel to the extended windings.

81. A test circuit as claimed in Claim 80 where extra conductors are placed in the endmost half-wavelengths, without secondary windings, to maintain the spatial periodicity of the conductors in the test circuit.

82. A test circuit as claimed in Claim 80 where extra conductors are placed at the ends of the sensing elements to maintain the spatial periodicity of conductors in the test circuit.

83. A test circuit as claimed in Claim 80 where extra conductors are placed between the inner coils for pairs of differential elements to ensure that each individual coil is surrounded by the same conductor pattern.

84. A test circuit as claimed in Claim 83 where the individual coils for the differential elements are separated by more than a coil length.

85. A test circuit as claimed in Claim 80 where at least one of the differential elements is rotated so that the coils are offset equal distances on either side of the centerline of a half wavelength of a primary meander.

86. A test circuit as claimed in Claim 85 where the rotated differential element is perpendicular to the extended windings of the primary.

87. A test circuit as claimed in Claim 77 where measurements grids with one or more dimensions are generated in advance and used as databases to look up and interpolate the electrical and geometric properties of interest at the location measured by each individual sensing element.

88. A test circuit as claimed in Claim 87 where the electrical and geometric properties at each sensing element location are correlated with dependent properties of interest.

89. A test circuit as claimed in Claim 87 where the array is scanned to build images of electrical properties across the surface of a part.

90. A test circuit as claimed in Claim 88 where multiple frequencies are used to measure property variations with depth at each sensing element.

91. A test circuit as claimed in Claim 89 where multiple frequencies are used to create three-dimensional images of properties.

92. A test circuit comprising:

a meandering primary winding having extended portions for imposing a spatially periodic magnetic field of at least two spatial wavelengths in a test substrate; and

a sensing winding array of sensing elements, with a sensing element positioned every half wavelength of at least two spatial wavelengths between respective adjacent extended portions of the primary winding for sensing the response of the test substrate to the imposed magnetic field, the sensing elements including sensing coils for linking flux over incremental areas between adjacent extended portions, at least one absolute sensing coil every half wavelength and at least two differential sensing coils every other half

wavelength, distance between sensing coils within an adjacent pair of extended portions being increased each wavelength, each individual sensing coil having separate output connectors, distances from the ends of the sensing coils to connectors between the extended portions of the primary being substantially constant as the distance between the sensing coils is increased.

93. A test circuit as claimed in Claim 87 wherein the extended portions of the primary winding are formed by individual drive coils having parallel extended portions with every other drive coil connected in series on one side of the primary and the remaining drive coils connected in series on the opposite side of the primary.

94. A test circuit as claimed in Claim 77 that is conformable to inspect curved parts.

95. A test circuit as claimed in Claim 77 placed on a curved and compliant substrate to inspect a curved part.

96. A test circuit as claimed in Claim 89 where the part being scanned is an engine disk slot.

97. A test circuit as claimed in Claim 96 where two or more sensing coils are located at the same position along half-wavelength but in different half-wavelengths of the primary to provide property measurement redundancy at a specific test material location with a single measurement scan.

98. A test circuit as claimed in Claim 97 where five sensing coils are located at the same position along a half wavelength but in different half wavelengths of the primary.

99. A test circuit as claimed in Claim 78 further comprising connection leads to the sensing element that are offset from the centerline of the half meander, a second loop having extended portions substantially parallel to the connection leads and symmetrically located on the opposite side of the centerline, and with a differential connection between the sensing element and the second loop.

100. A test circuit as claimed in Claim 80 further comprising connection leads to the sensing element that are offset from the centerline of the half meander, a second loop having extended portions substantially parallel to the connection leads and symmetrically located on the opposite side of the centerline, and with a differential connection between the sensing element and the second loop.

101. An eddy-current sensor for creating a spatially periodic magnetic field of at least two periods comprising:

a primary winding having parallel extended winding segments and driven by an electric current; and

each half wavelength of the primary windings being formed by an individual drive coil having parallel extended portions with every other drive coil connected in series on one side of the primary and the remaining drive coils connected in series on the opposite side of the primary.

102. A method for creating a spatially periodic magnetic field, with at least two periods, for eddy current sensors comprising:

providing a primary winding of parallel extended winding segments, each parallel extended winding segments being formed by parallel extended portions of adjacent individual drive coils;

driving current through individual drive coils in alternating clockwise and counterclockwise directions such that current through immediately adjacent

extended portions of the drive coils are in common directions and a spatially periodic magnetic field, with at least two periods, is imposed in a test substrate.

103. A method as claimed in Claim 101 wherein a single pair of connector leads is connected to each set of primary winding half-wavelengths.

104. A method as claimed in Claim 102 further comprising providing parallel extended winding segments distributed over two planes, the extended windings of the primaries located over one another and the connectors between the extended portions of the primary windings offset by one half-wavelength.

105. A test circuit comprising a plurality of adjacent individual drive coils having parallel extended portions with current flow in any adjacent extended portions being in a common direction and all the drive coils together imposing a stationary periodic magnetic field, with at least two periods, in a test substrate.

106. A method for monitoring damage at a fastener comprising:

mounting a spatially periodic field eddy-current sensor to a test substrate near a fastener; and

sensing response of the test substrate to a magnetic field imposed by the eddy-current sensor.

107. A method as claimed in Claim 106 where the sensor is mounted under the head of the fastener.

108. A method as claimed in Claim 106 where the sensor is mounted between the layers of the structure attached by the fastener.

109. A method as claimed in Claim 106 where a sensor is mounted at both ends of the fastener.

110. A method as claimed in Claim 106 where the sensor is a circular spatially periodic field eddy-current sensor surrounding a fastener.

111. A method as claimed in Claim 106 where the damage is in the form of a crack.

112. A method as claimed in Claim 106 further comprising at least two circular spatially periodic field eddy-current sensors each mounted around a fastener and a single cable connects the drive and sense conductors to the data acquisition system.

113. A method as claimed in Claim 112 where the each sensor provides a separate output.

114. A method as claimed in Claim 113 where the output is an absolute property measurement.

115. A method as claimed in Claim 112 where the sense conductors from pairs of sensing elements are connected together to provide a differential measurement.

116. A method as claimed in Claim 112 where separate drive connections are made to each sensor.

117. A method as claimed in Claim 116 where the sense conductors are connected together to provide a common output connection.

118. A method as claimed in Claim 112 where the drive conductors are connected together to provide a common drive signal.

119. A method as claimed in Claim 118 where the sense conductors are connected together to provide a common output connection.

120. A method as claimed in Claim 106 where the sensor is mounted in a cylindrical support material shaped in the form of a washer for mounting under a fastener head.

121. A method as claimed in Claim 120 where the support material withstands compressive loads.

122. A method for estimating material properties from an inductive sensor comprising:

creating measurement grids that provide primary and sense windings in multiple layers;

storing the measurement grids as databases of sensor responses to a predetermined range of at least two unknown properties; and

using the databases to convert sensor responses into estimates of at least two unknown properties.

123. A method as claimed in Claim 122 where finite element modeling is used to generate databases of responses.

124. A method as claimed in Claim 122 where analytical models are used to generate databases of responses.

125. A method as claimed in Claim 122 where finite difference modeling is used to generate databases of responses.

126. A method of fabricating a damage standard comprising:

attaching an electromagnetic sensor to a critical surface of test material;

mechanically loading the test material and measuring a change in the electrical properties under the surface of the sensor; and

removing the mechanical load when the change in electrical properties indicates a prescribed level of damage.

127. A method as claimed in Claim 126 where the damage is a fatigue crack.

128. A method as claimed in Claim 126 where the sensor is a spatially periodic field eddy-current sensor and the test material is a metal.

129. A method as claimed in Claim 128 where the sensor is flexible for conforming to the shape of the surface of the test material.

130. A method as claimed in Claim 129 where the sensor is an array with multiple sensing elements for producing a spatial image of the damage.

131. A method as claimed in Claim 126 where the sensor is a dielectrometer and the test material is a dielectric material.

132. A method as claimed in Claim 126 further comprising the use of a temperature measurement sensor to correct for electrical property variations with temperature.

133. A method as claimed in Claim 126 further comprising the use of multiple sensors to monitor multiple regions.

134. A method as claimed in Claim 133 where the sensors include arrays with multiple sensing elements for producing spatial images of the damage.

135. A method as claimed in Claim 127 further comprising the use of a sensor to monitor the change in crack length with the number of fatigue cycles.

136. A method as claimed in Claim 127 further comprising the use of multiple frequency measurements to monitor crack depth.

137. A method as claimed in Claim 127 where the damage is pre-crack damage.

138. A method as claimed in Claim 127 further comprising mounting the sensor between layers of the test material.

139. A method as claimed in Claim 128 further comprising the use of a sealant to provide mechanical support.

140. A method as claimed in Claim 126 further comprising shaping the test material to create a stress distribution so that fatigue damage initiates under the sensor.

141. A method as claimed in Claim 140 where the test material is formed into a dogbone shape and the center section is thinned to localize fatigue damage.

142. A method as claimed in Claim 141 where the test material further comprises reinforcement ribs on the edges.

143. A method as claimed in Claim 142 where the test material further comprises radius cutouts on both sides of the thinned section.

144. A method as claimed in Claim 140 where the test material further comprises radius cutouts on both sides of the thinned section.

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